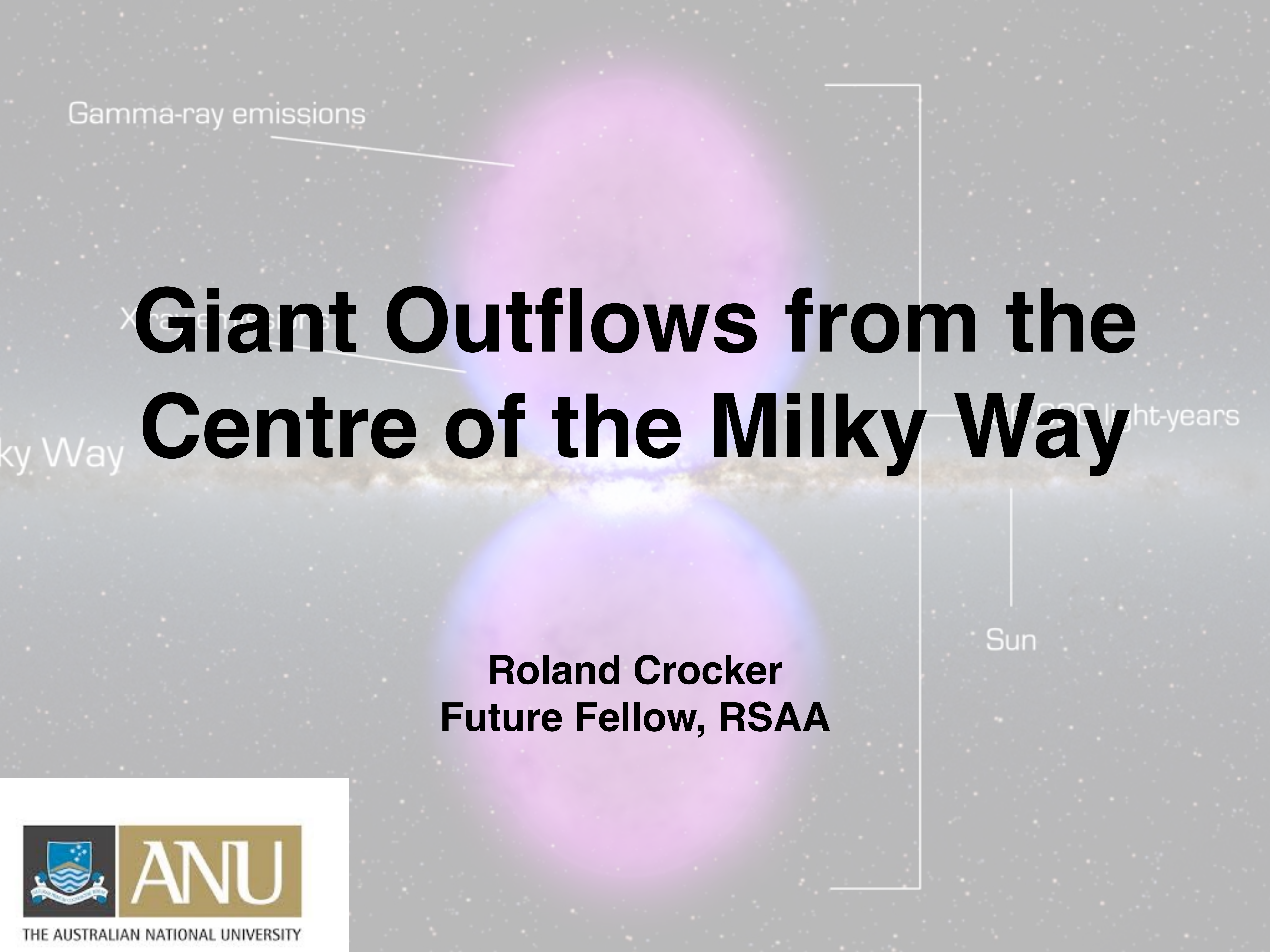


Giant Outflows from the Centre of the Milky Way

Roland Crocker
Future Fellow, RSAA

THE AUSTRALIAN NATIONAL UNIVERSITY

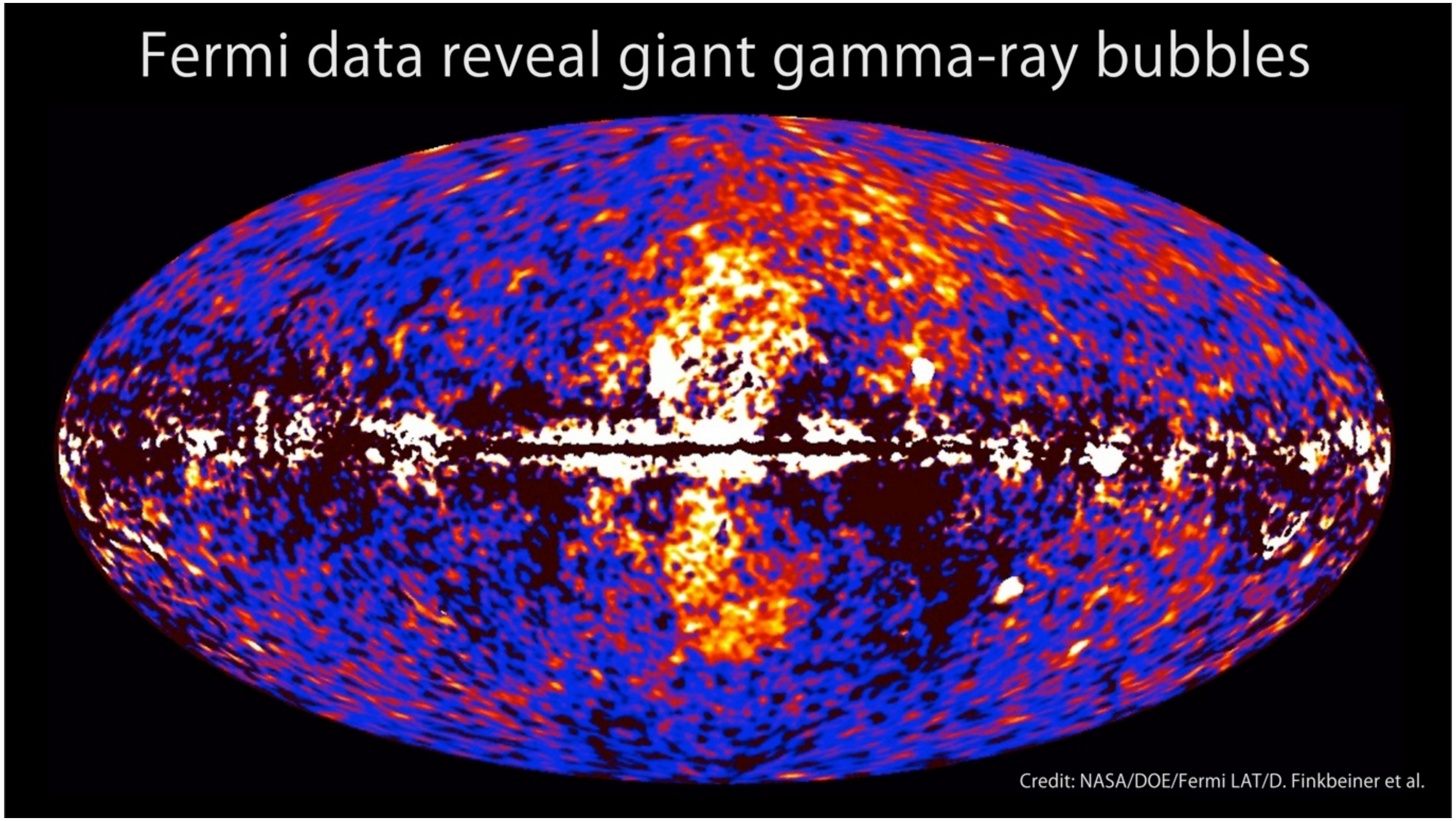
Collaborators

- Geoff Bicknell, RSAA

- Ettore Carretti, Cagliari Observatory

- Andrew Taylor, Dublin Institute for Advanced Studies

Fermi Bubbles



Su, Slatyer and Finkbeiner 2010 (ApJ)

Fermi Bubbles

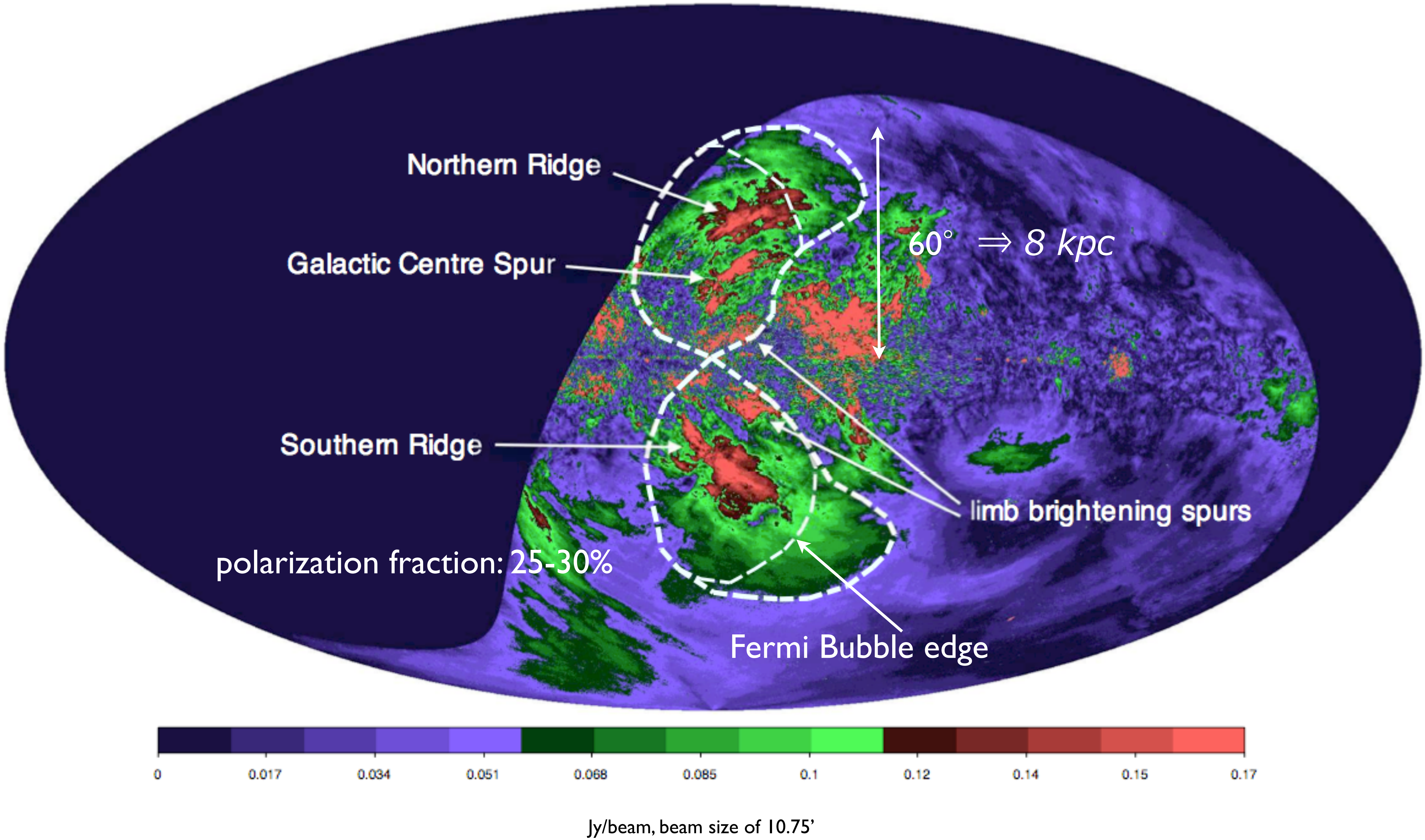
- 2 x 10^{37} erg/s [1-100 GeV]
- hard spectrum, but spectral down-break below ~ GeV in SED, cut-off ~100 GeV
- uniform projected intensity
- sharp edges
- coincident emission at other wavelengths
- vast extension: ~7 kpc from plane
- $\gtrsim$ few 10^{55} erg

S-PASS Survey

2.3 GHz RC polarization survey of southern sky with Parkes 64-m single disk, 184 MHz BW

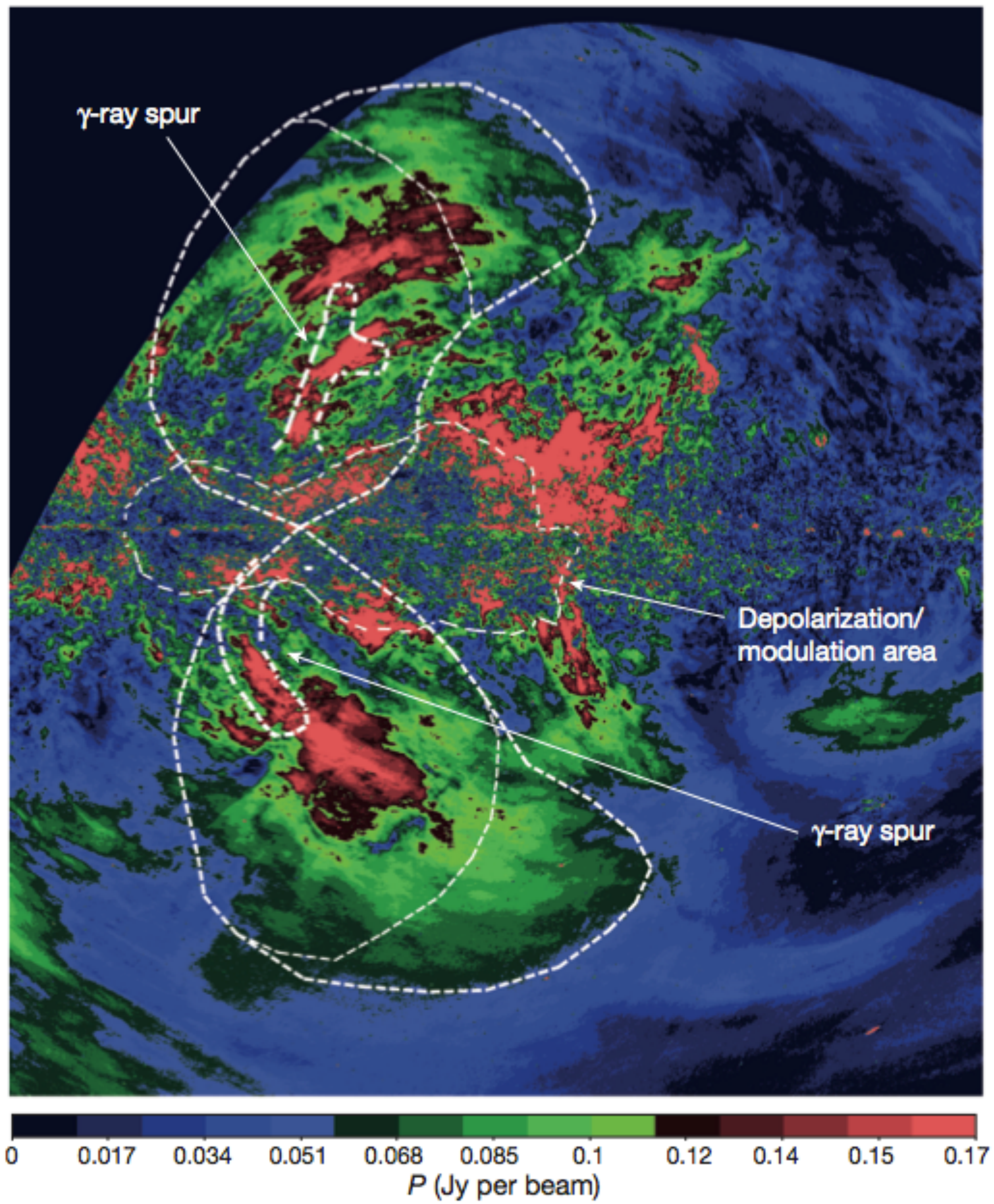
'The Dish', 52 years old

The 'S-PASS Lobes'



Carretti, Crocker et al. 2013

The 'S-PASS Lobes'



Carretti, Crocker et al. 2013

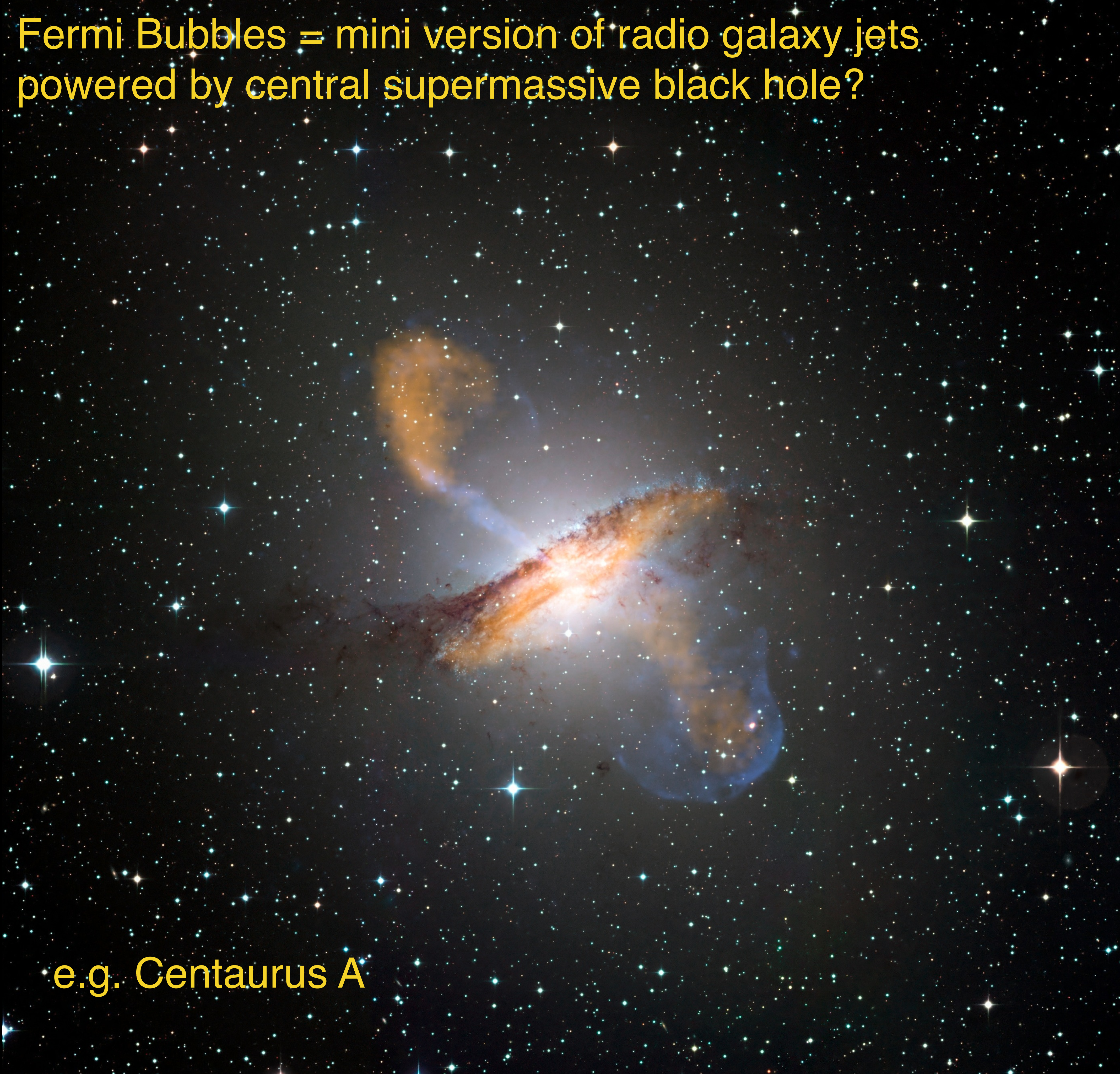
Fermi Bubbles: Two Interlocking Questions

Q1. What energizes the outflow?

Recent Seyfert-like activity of Sgr A*

OR Nuclear star formation **OR** tidal disruption of stars by SMBH **OR** dark matter **OR** ….

Fermi Bubbles = mini version of radio galaxy jets powered by central supermassive black hole?



e.g. Centaurus A

Fermi Bubbles = nuclear starburst with outflowing winds?

e.g. M82

Energetics

- The (photon) Eddington luminosity of Sgr A* ($4 \times 10^6\ M_{Sun}$): 5×10^{44} erg/s
- Star formation in the CMZ at a rate ~$0.05\ M_{Sun}$/yr
- This injects mechanical power (supernova explosions, stellar winds) of

$$P_{mech} \sim 0.08\ M_{Sun}/\text{yr} \times 1\ \text{SN}/(90\ M_{Sun}) \times 10^{51}\ \text{erg/SN}$$

$$= 3 \times 10^{40}\ \text{erg/s}$$

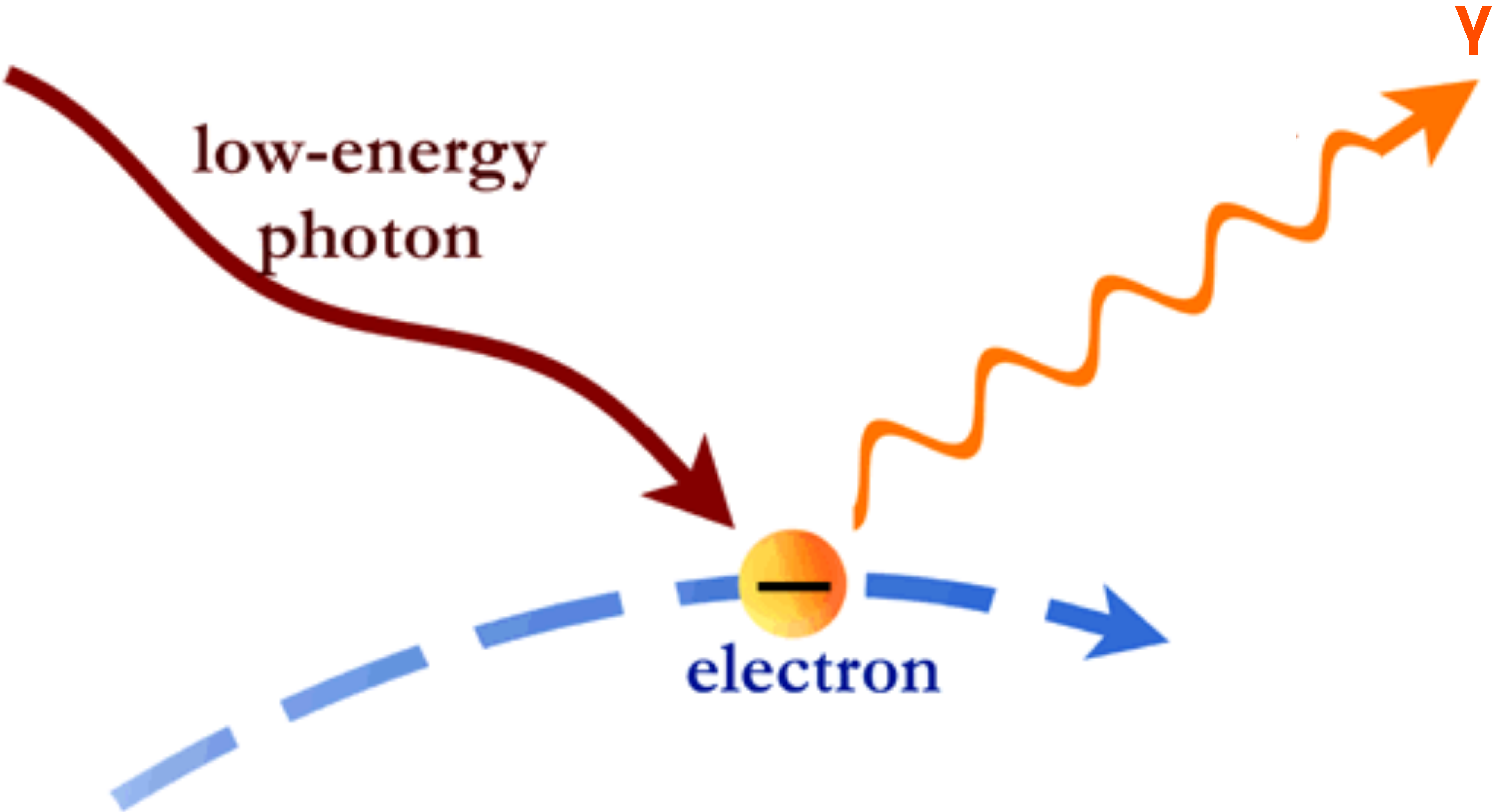
…the GC is not a Starburst

Fermi Bubbles: Two Interlocking Questions

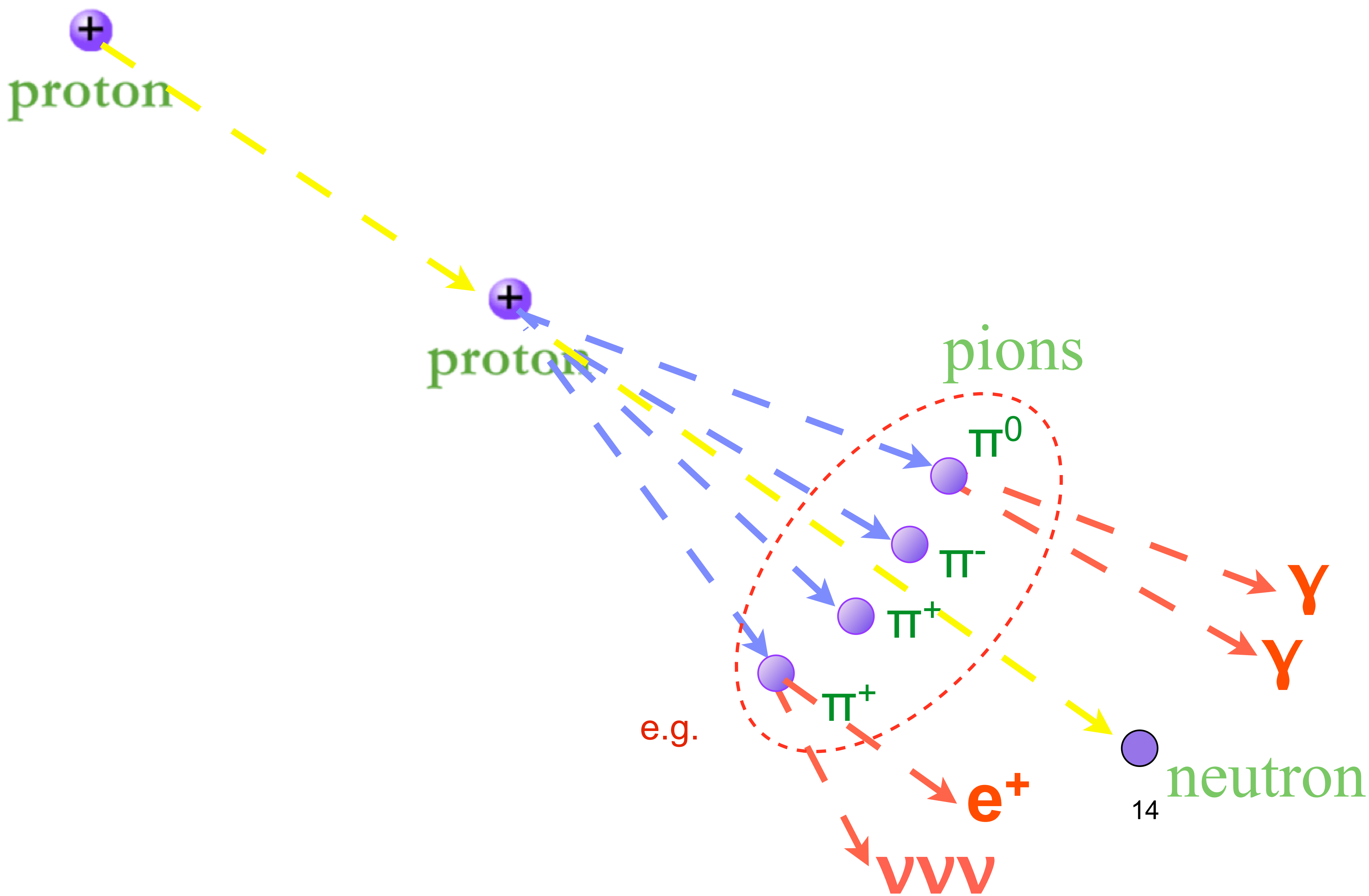
Q2. What is the radiation mechanism?

‘**leptonic**’: Cosmic ray electrons/Inverse Compton emission

Inverse Compton Scattering



pp → Pion Decay → secondaries



Leptonic Scenar…

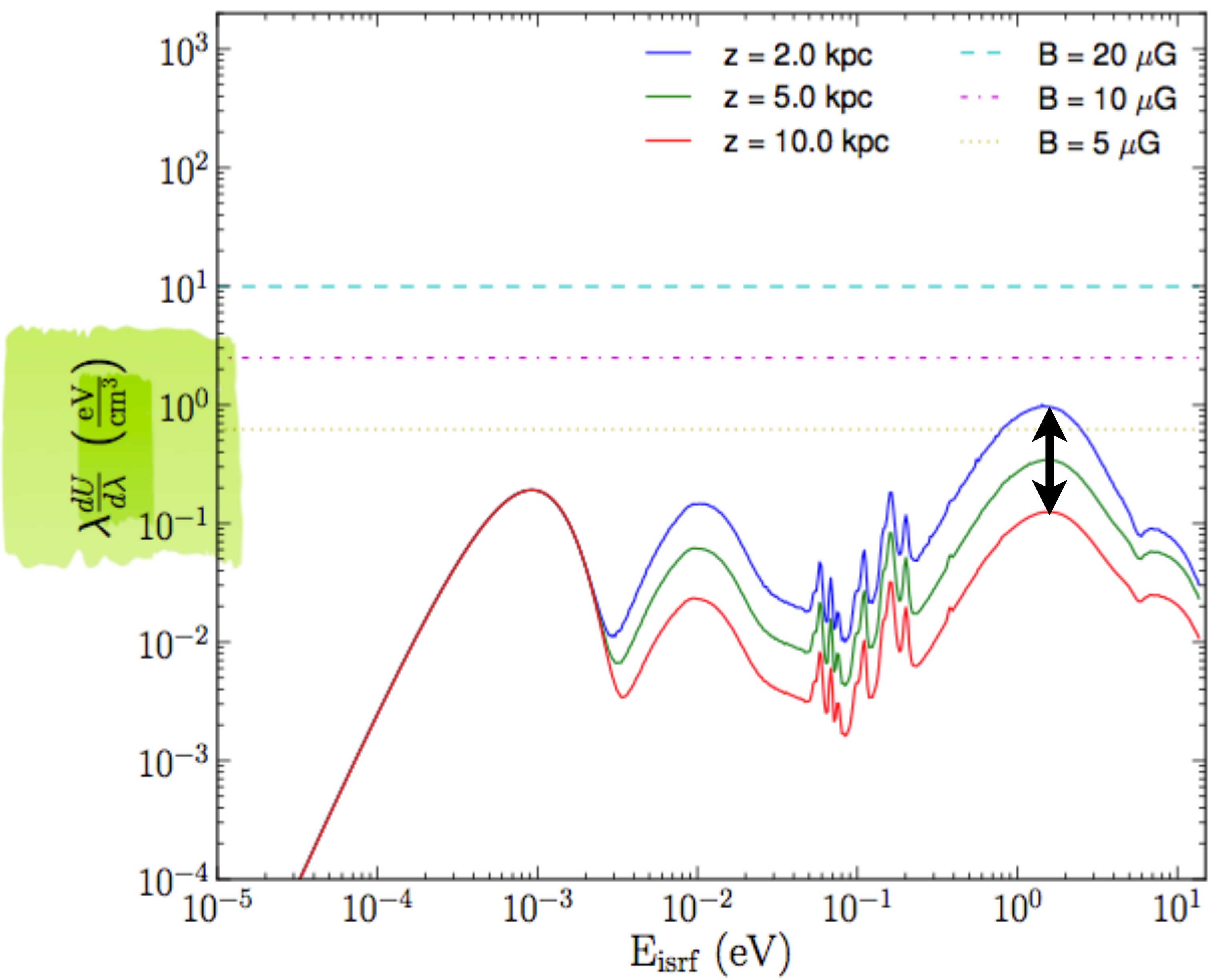
- ~GeV γ-ray em… …on … ISRF by hy… …opula… spect… …ctron
- …ation… …-radiates into …wave …

BUT… …ng time (Myr) ⇒ near- … transport OR in situ …eration with fast expansion (v > 2000 km/s)

Why is γ-ray spectrum invariant (hardening) with altitude?

Why isn't there X-ray brightening of edges?

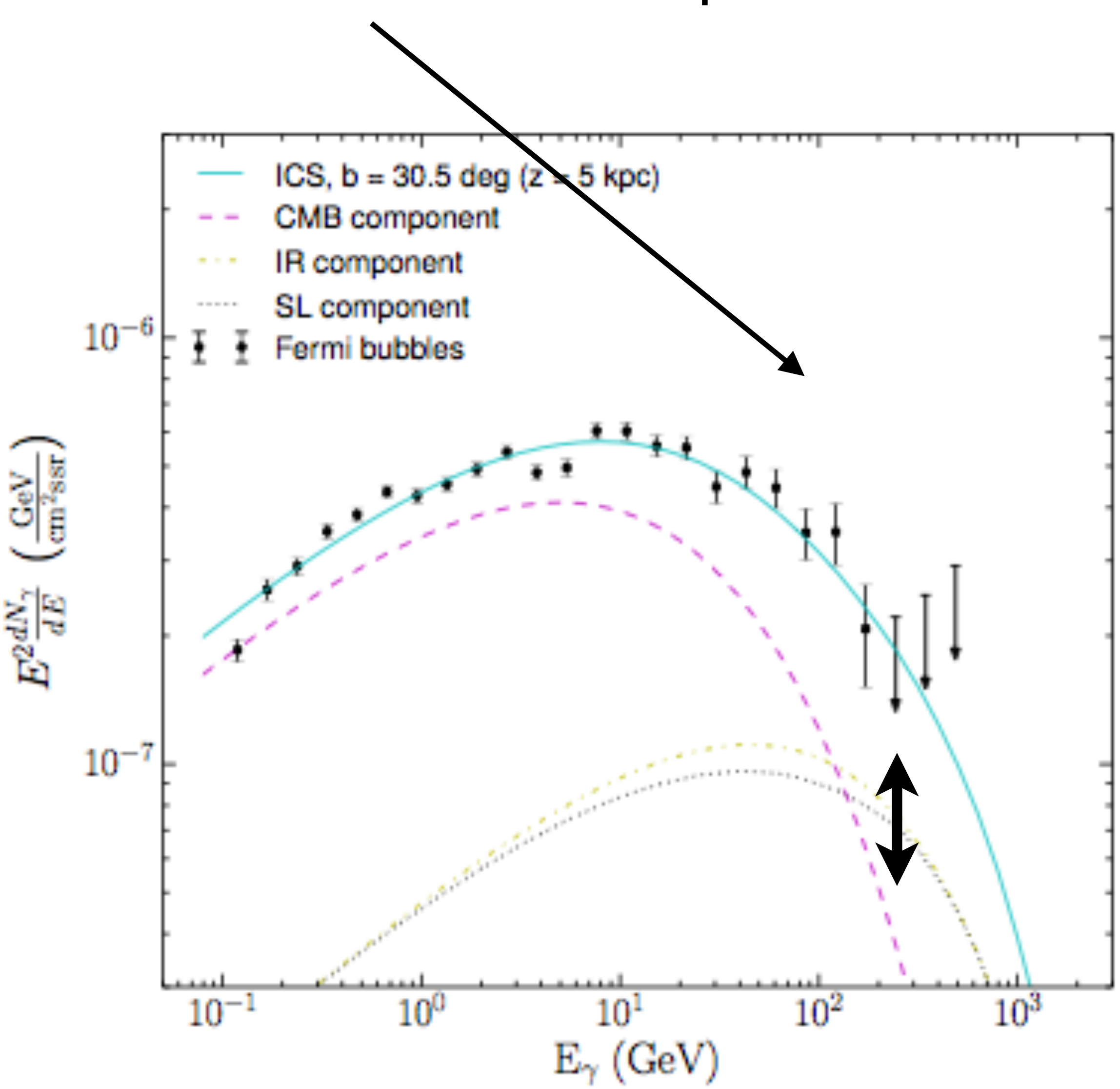
Leptonic Scenarios

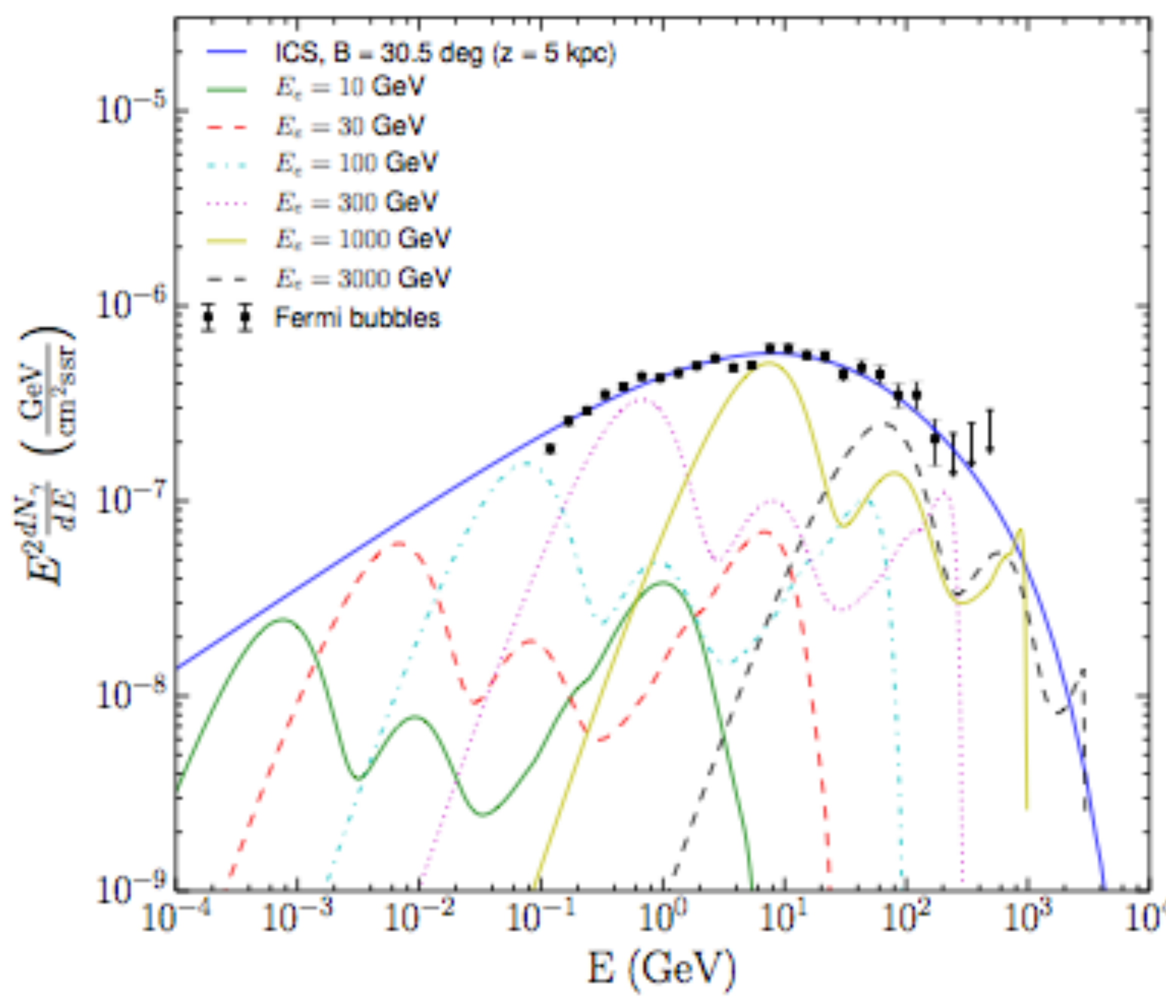


Ackermann et al. 2014 *Fermi* collab

Leptonic Scenarios

calculated at 5 kpc



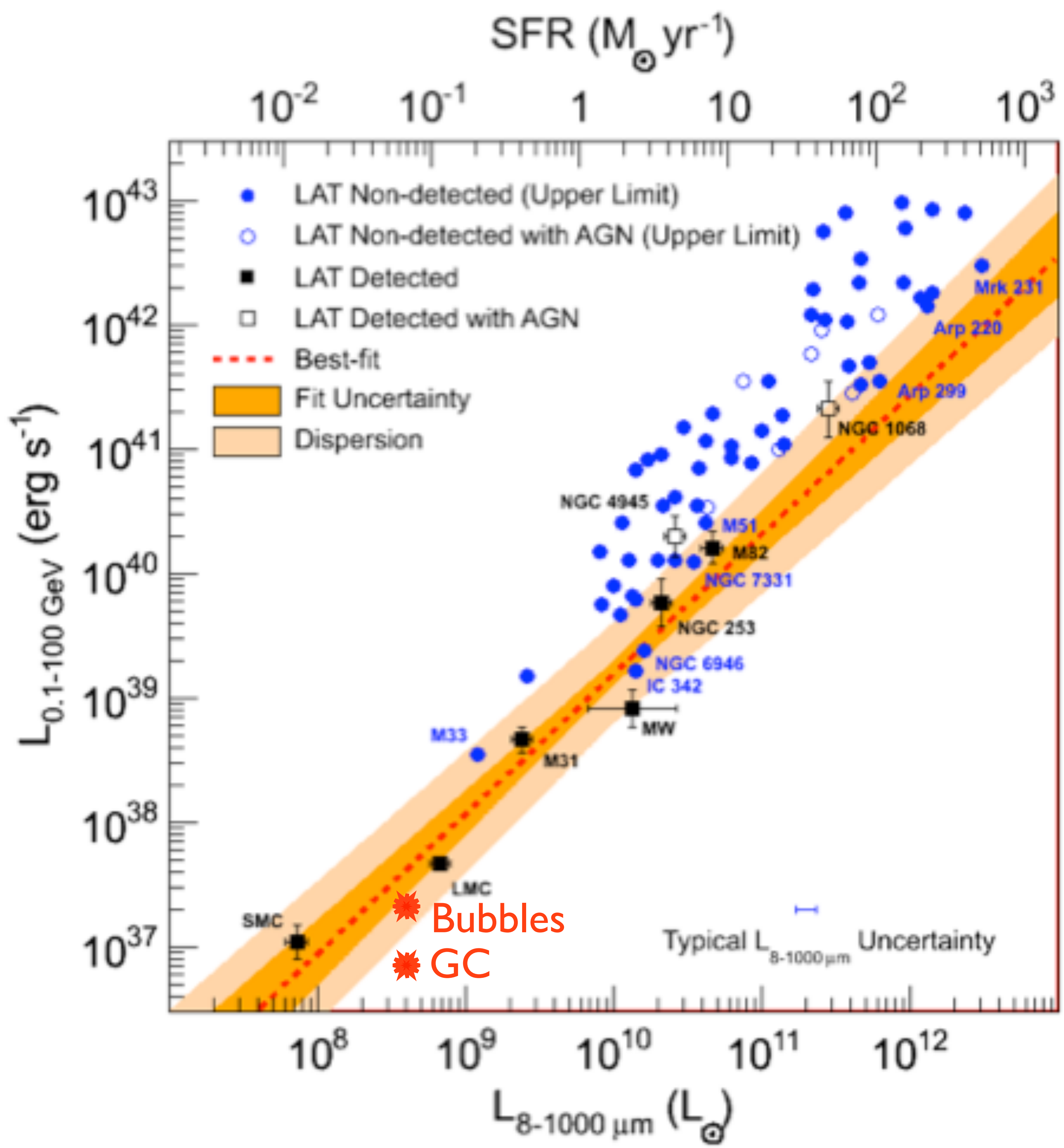


Ackermann et al. 2014 *Fermi* collab

Hadronic Scenario

Crocker & Aharonian PRL 2011

- Bubbles' gamma-ray luminosity requires a source of protons of power ~10^{39} erg/s *in saturation*
- This *is* the power supplied by nuclear SF to cosmic rays that escape the GC



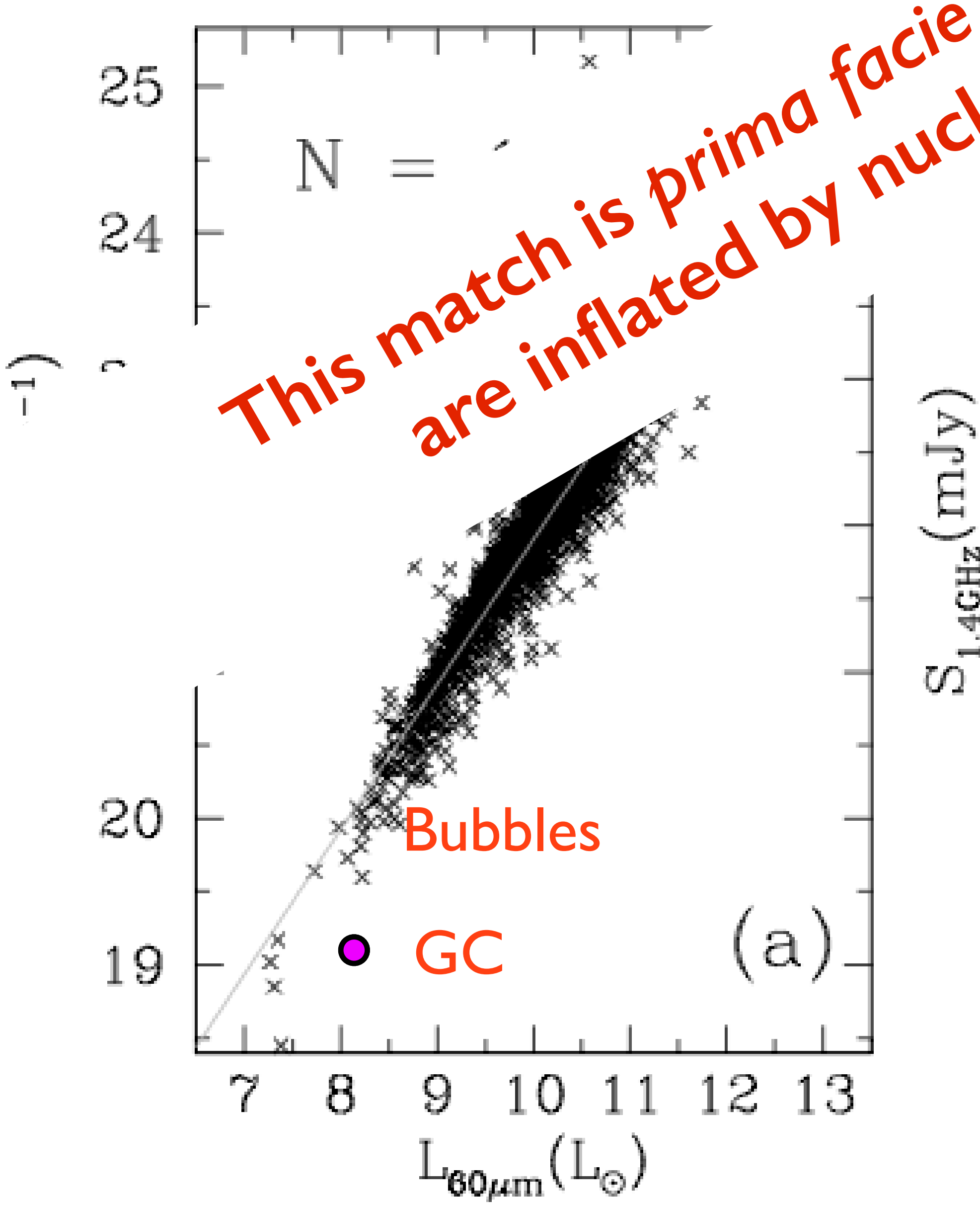
Ackermann et al. 2012 (*Fermi collab*)

Fig. 1. Gamma-ray luminosity (0.1-100 GeV) versus total IR luminosity (8-1000μm).

FIR-R

Yun et al. 2001 ApJ 554, 8

This match is *prima facie* evidence the Bubbles are inflated by nuclear star-formation

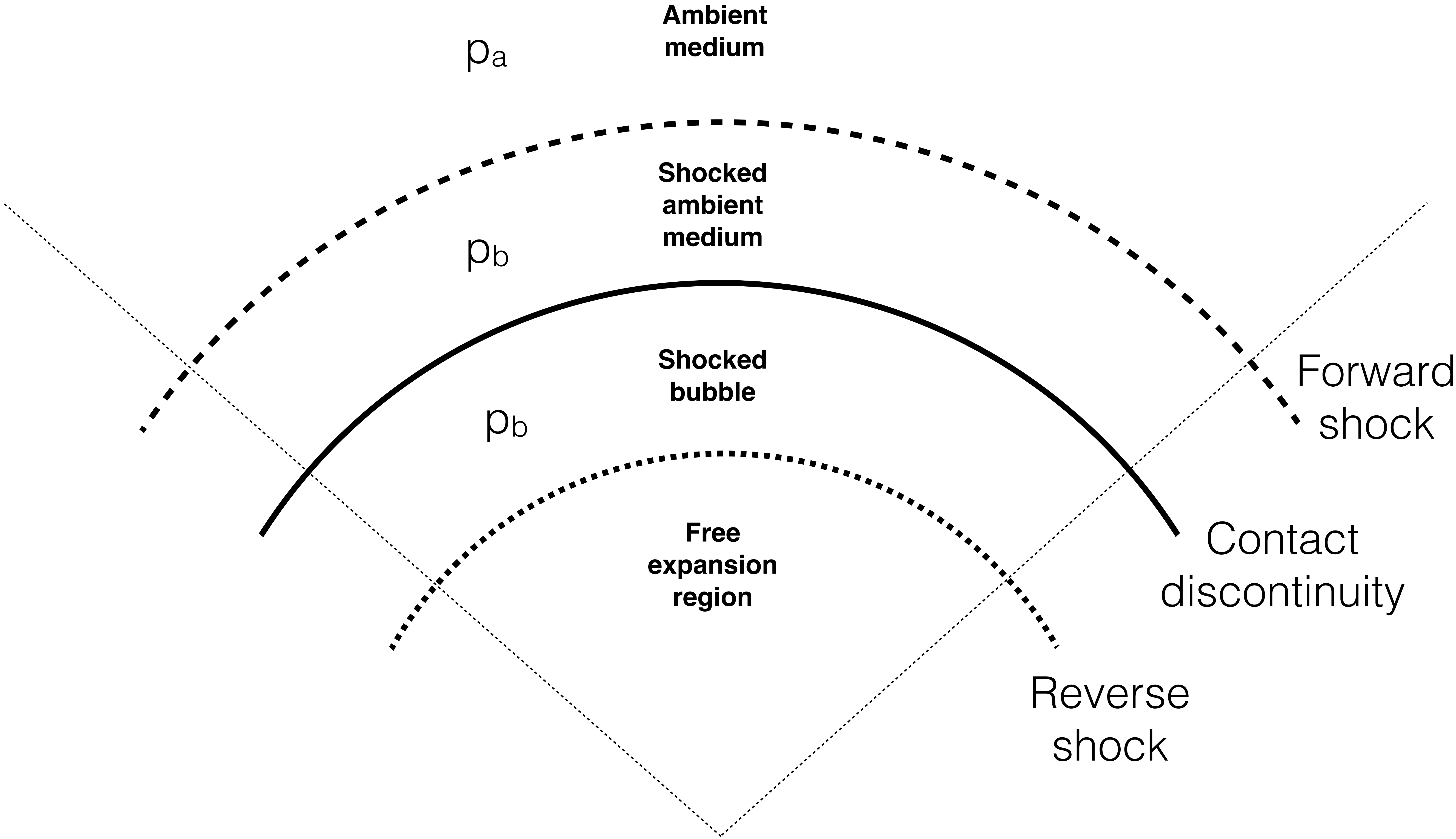


$L_{1.4\,GHz}$ = 1. Watt/Hz

$L_{60\mu m} = 1.3 \times 10^8\ L_\odot$

The Fermi Bubbles *as Bubbles*

Crocker, Bicknell, Taylor et al.

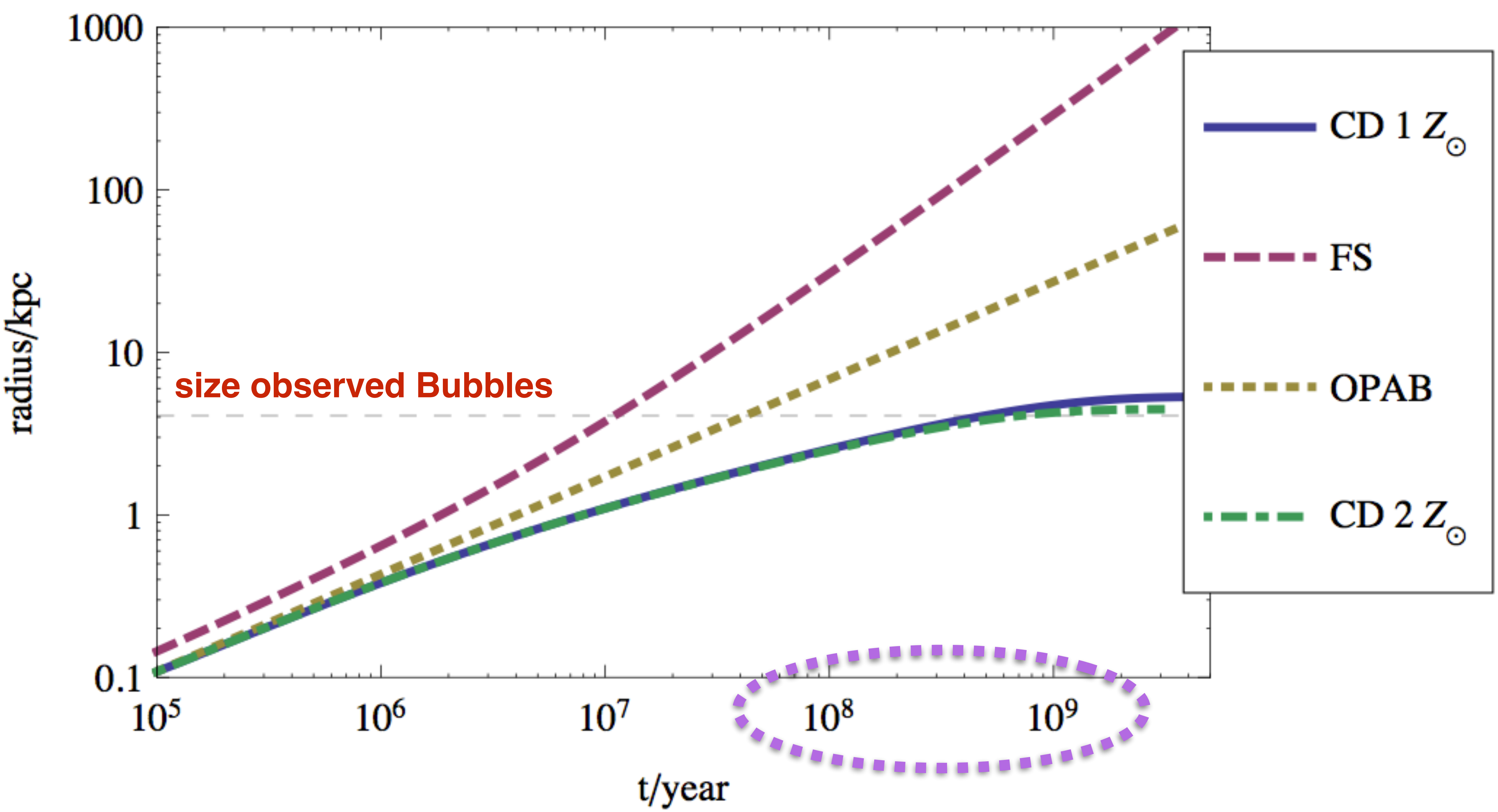

Ambient medium
p_a
Shocked ambient medium
p_b
Shocked bubble
p_b
Free expansion region
Forward shock
Contact discontinuity
Reverse shock

Giant Shocks in the Fermi Bubbles

- General scenario: adiabatically-expanding nuclear wind…
- Reverse shock where $P_{ram} = P_{pls}$
- Have to incorporate gravity, halo pressure & cooling

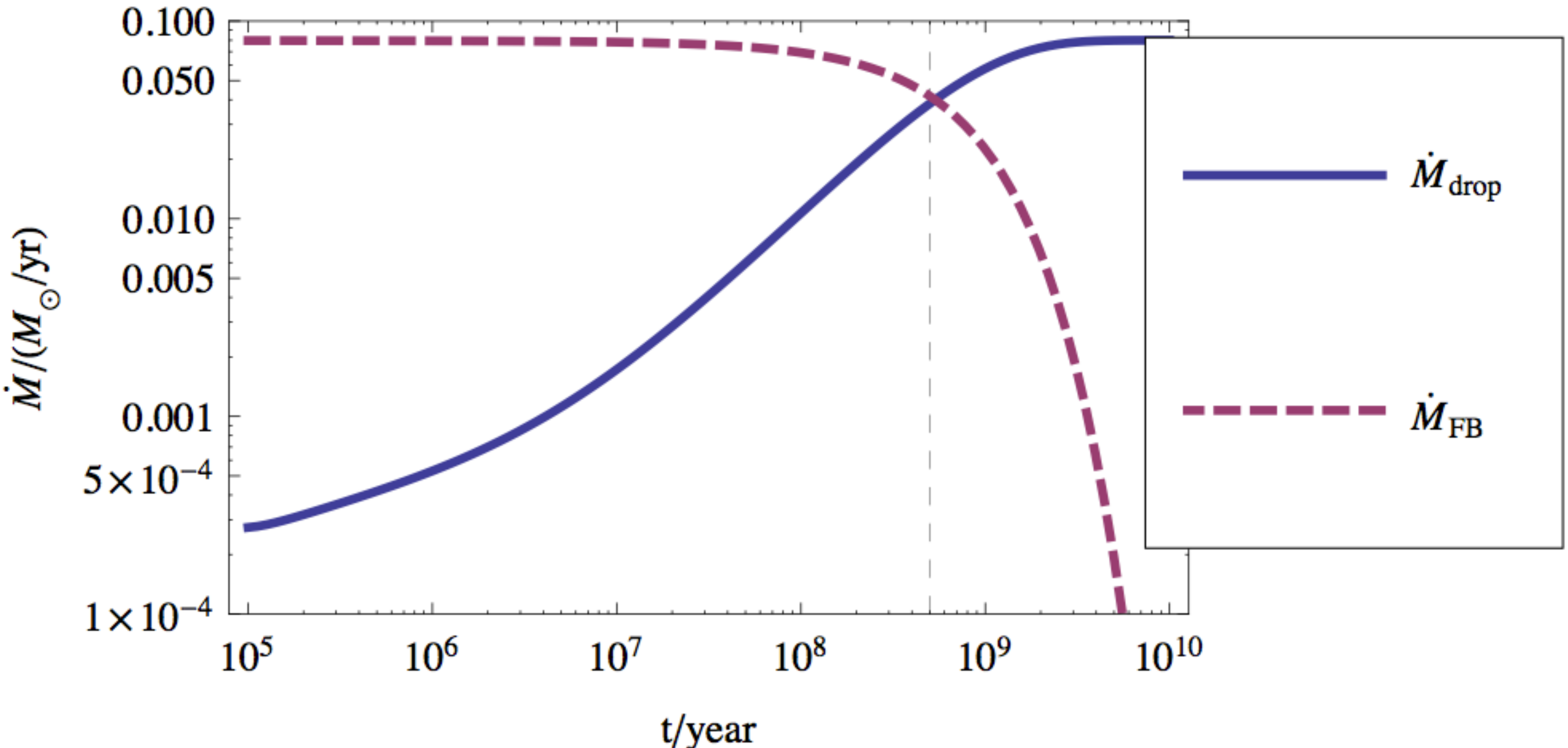
Crocker, Bicknell, Taylor et al. *in preparation*

Expansion of a radiative bubble into finite (const) pressure medium

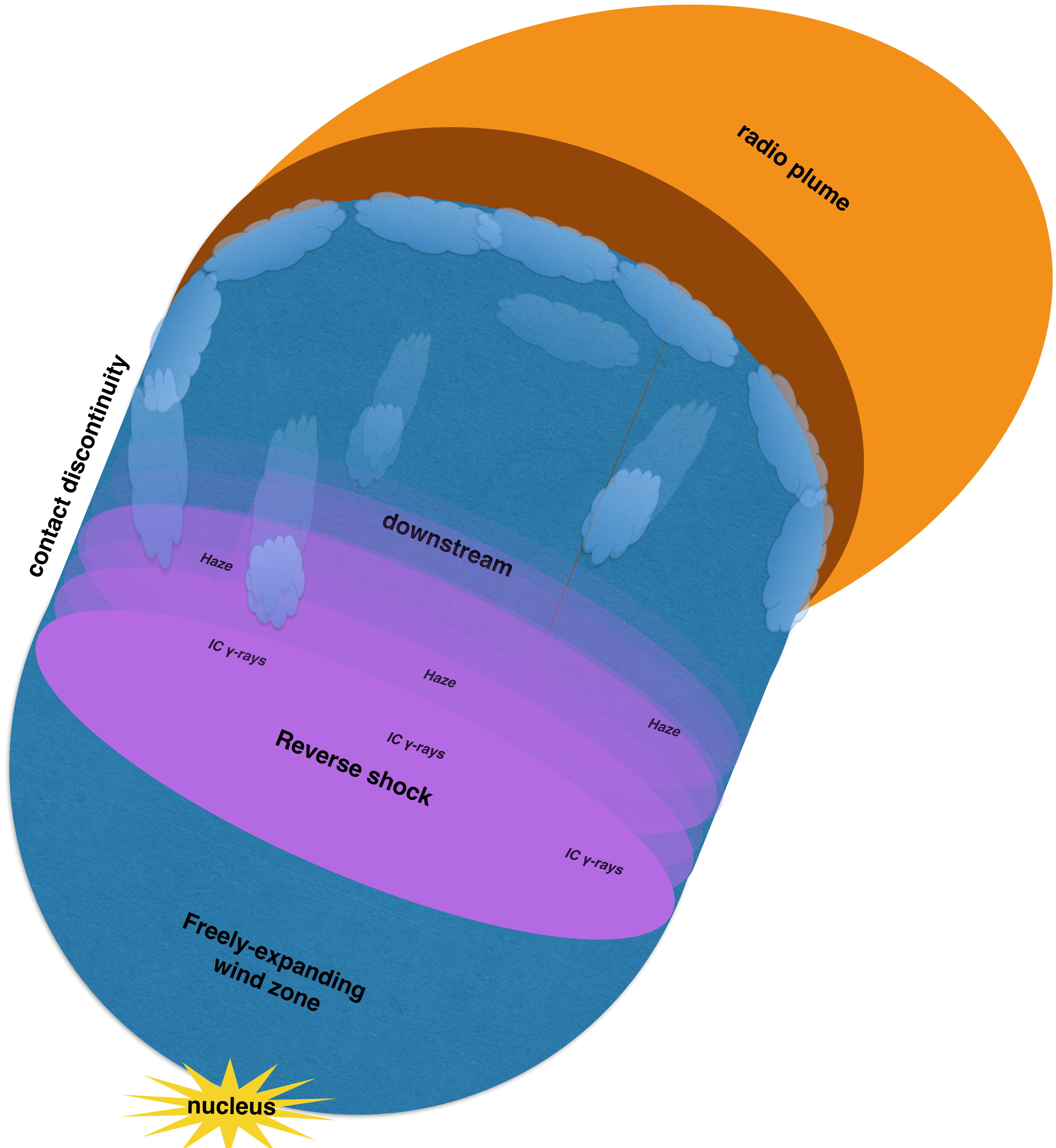


Crocker, Bicknell, Taylor et al.

Expansion of a radiative bubble into finite (const) pressure medium



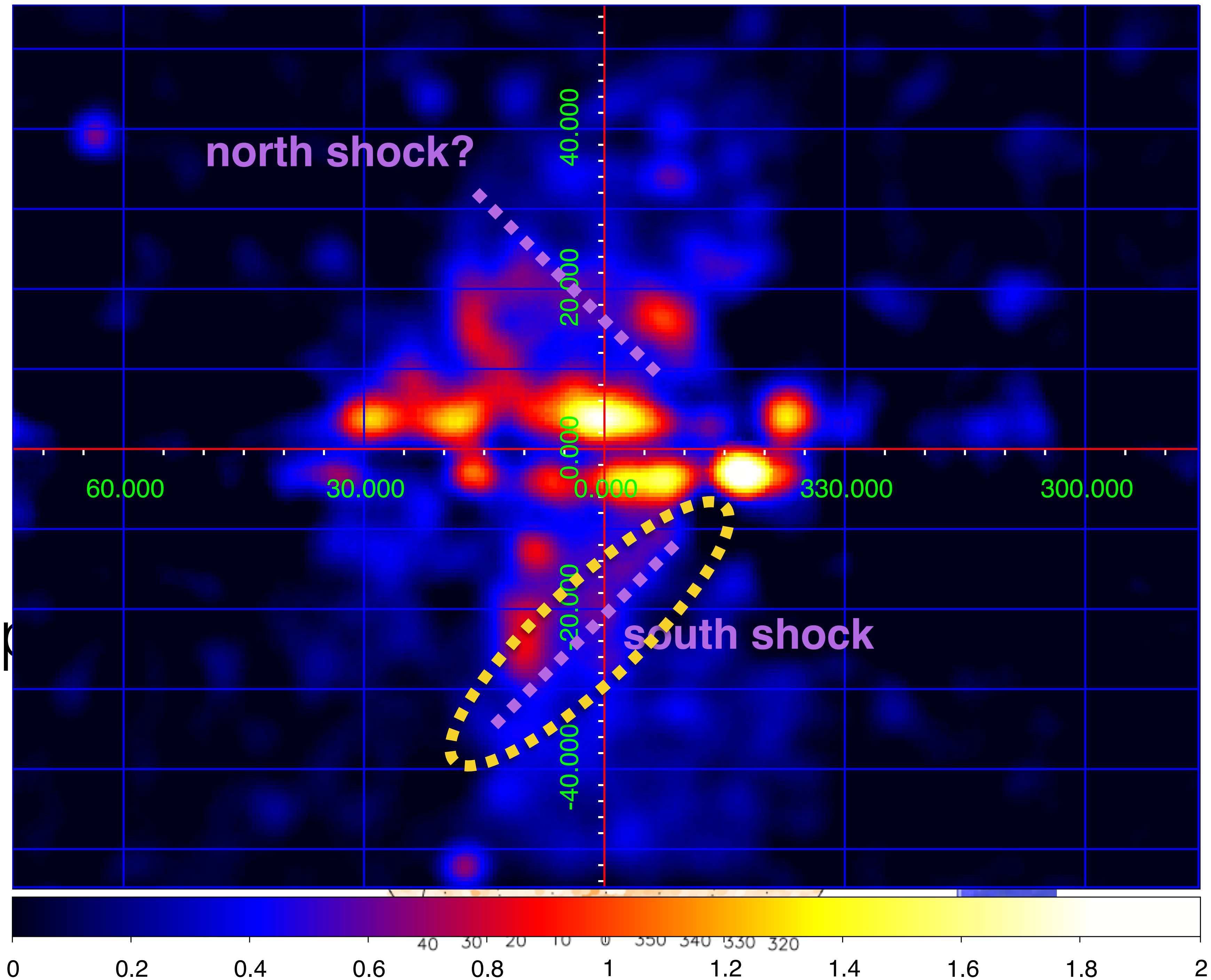
Crocker, Bicknell, Taylor et al.


radio plume
contact discontinuity
downstream
Haze
IC γ-rays
Haze
IC γ-rays
Haze
Reverse shock
IC γ-rays
Freely-expanding
wind zone
nucleus

Evidence for Shocks?

Crocker, Bicknell, Taylor et al.

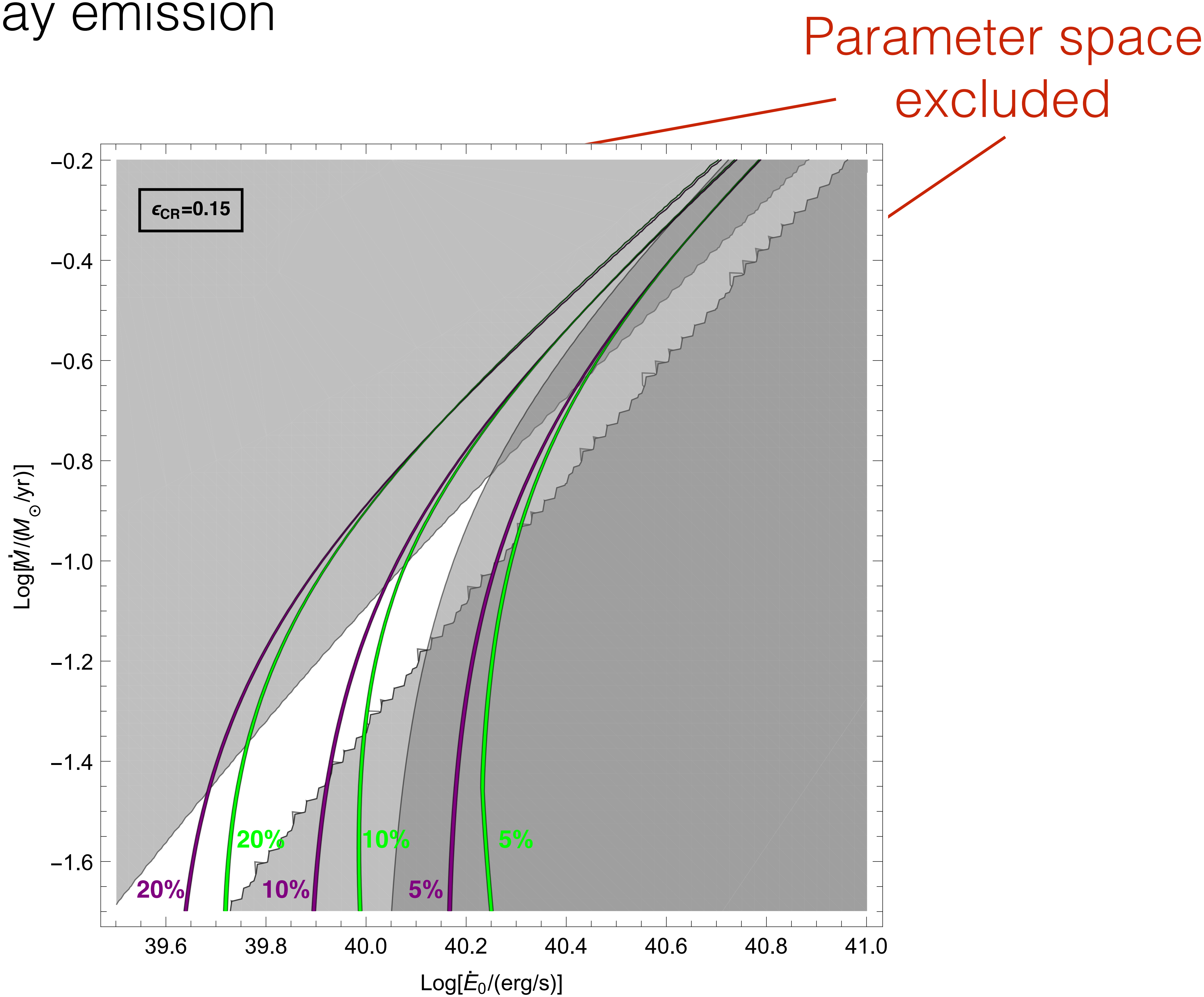
H-alp


north shock?
south shock
40.000
20.000
0.000
-20.000
-40.000
60.000
30.000
0.000
330.000
300.000
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2

Predicted Emission

Crocker, Bicknell, Taylor et al.

Gamma-ray emission



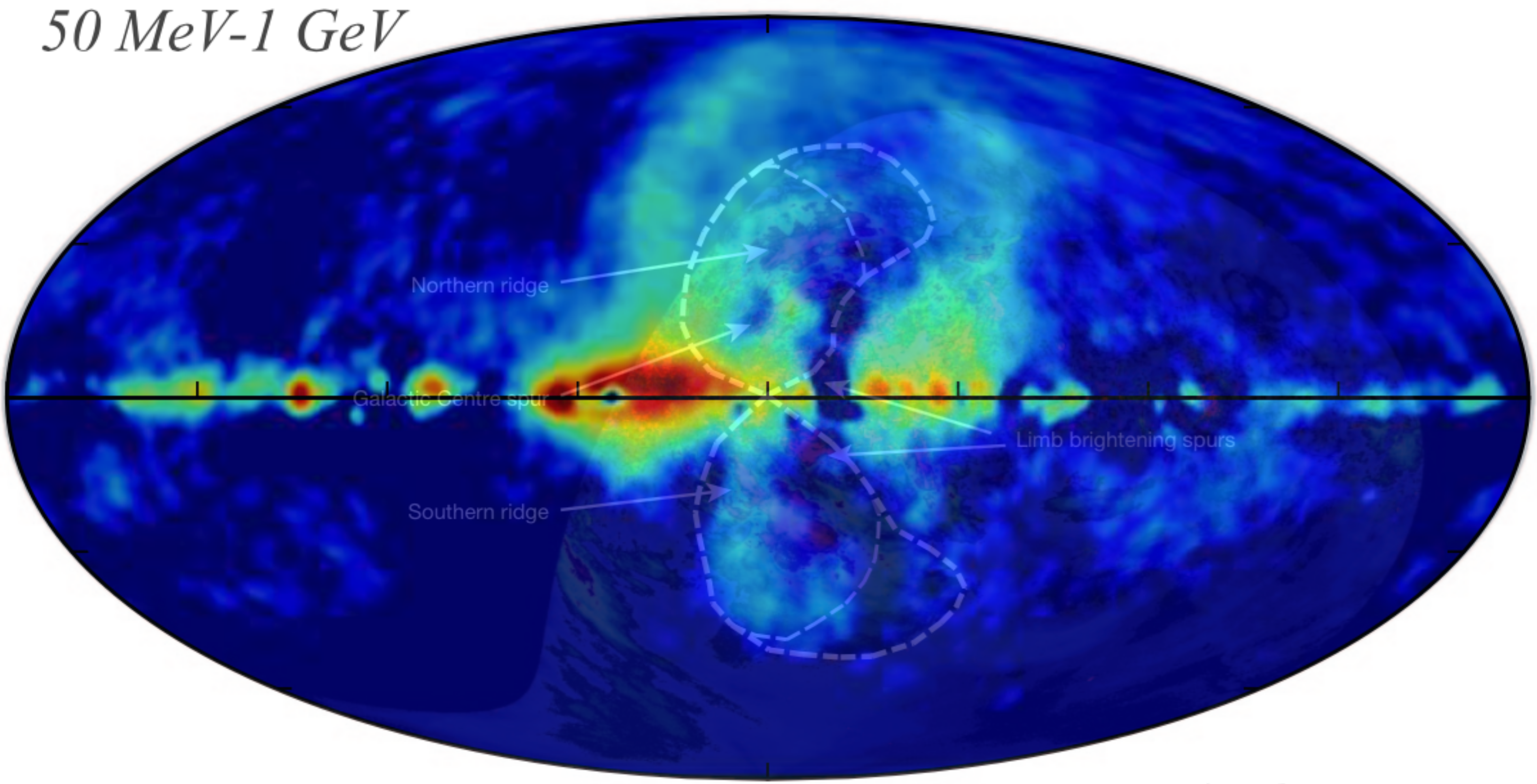
Crocker, Bicknell, Taylor et al. *in preparation*

Forward Shock?

Crocker, Bicknell, Taylor et al.

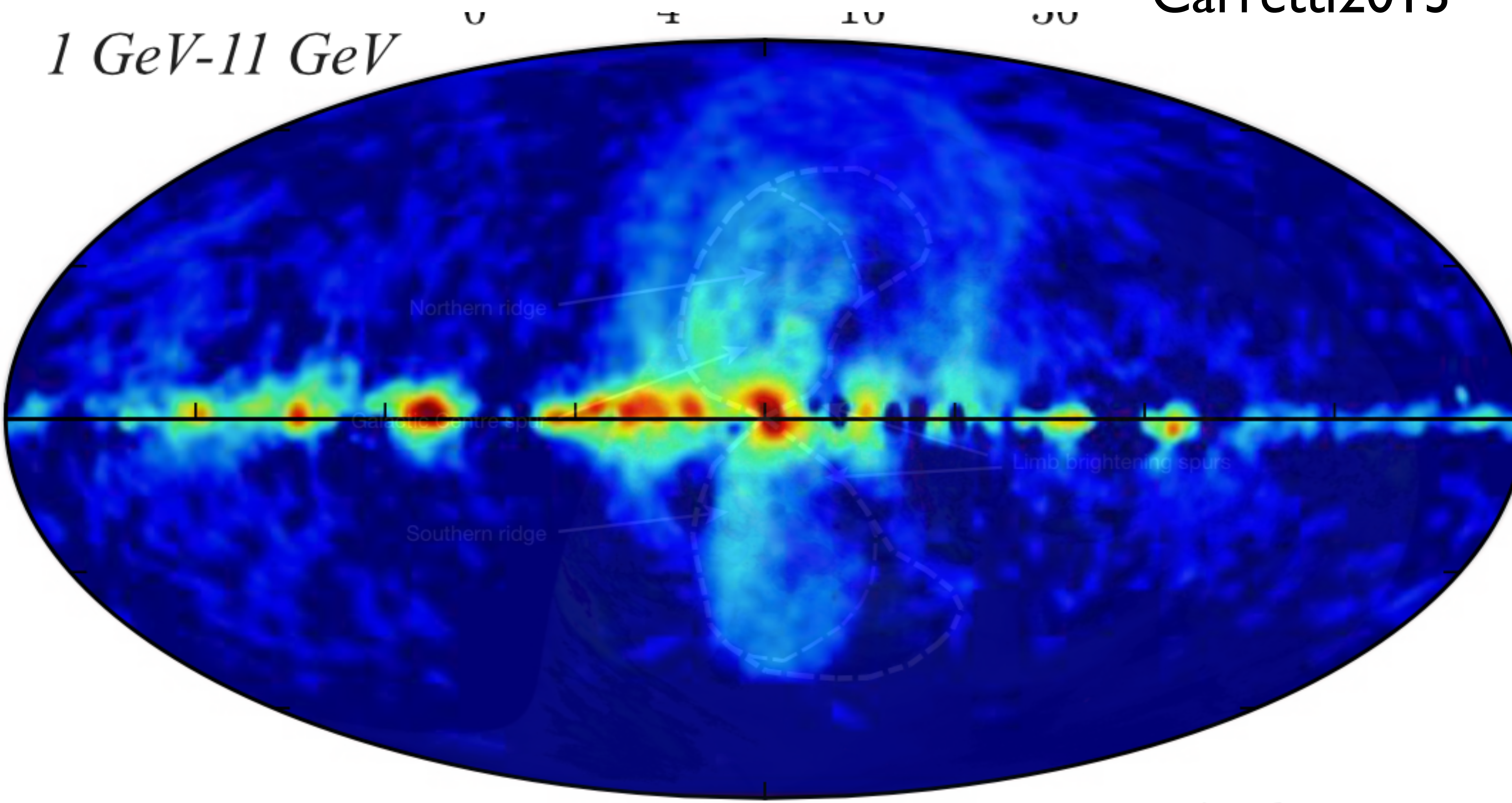
Casandjian2015

S-PASS 2.3 GHz
polarzd intensity
Carretti2013



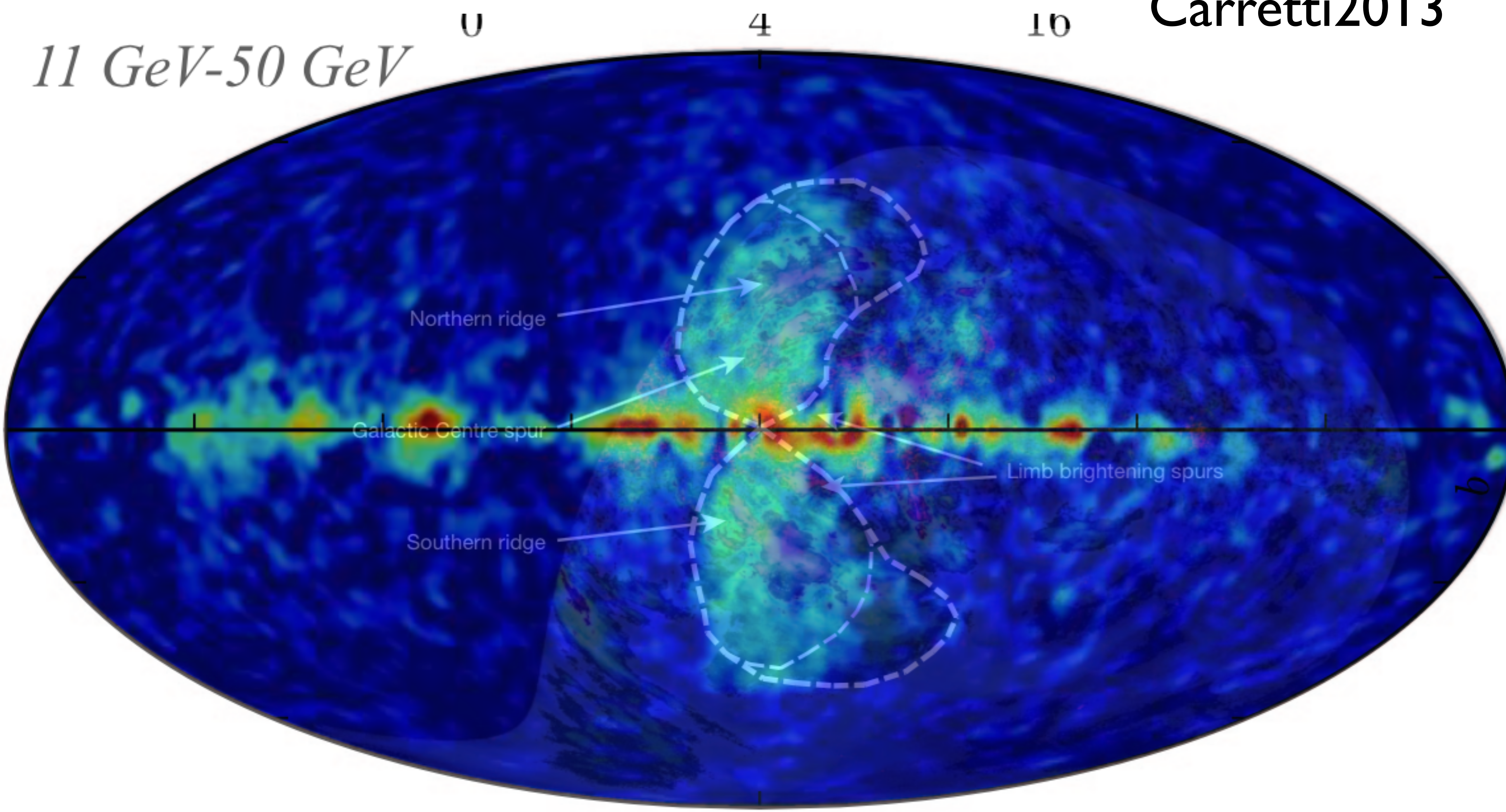
Casandjian2015

S-PASS 2.3 GHz
polarzd intensity
Carretti2013

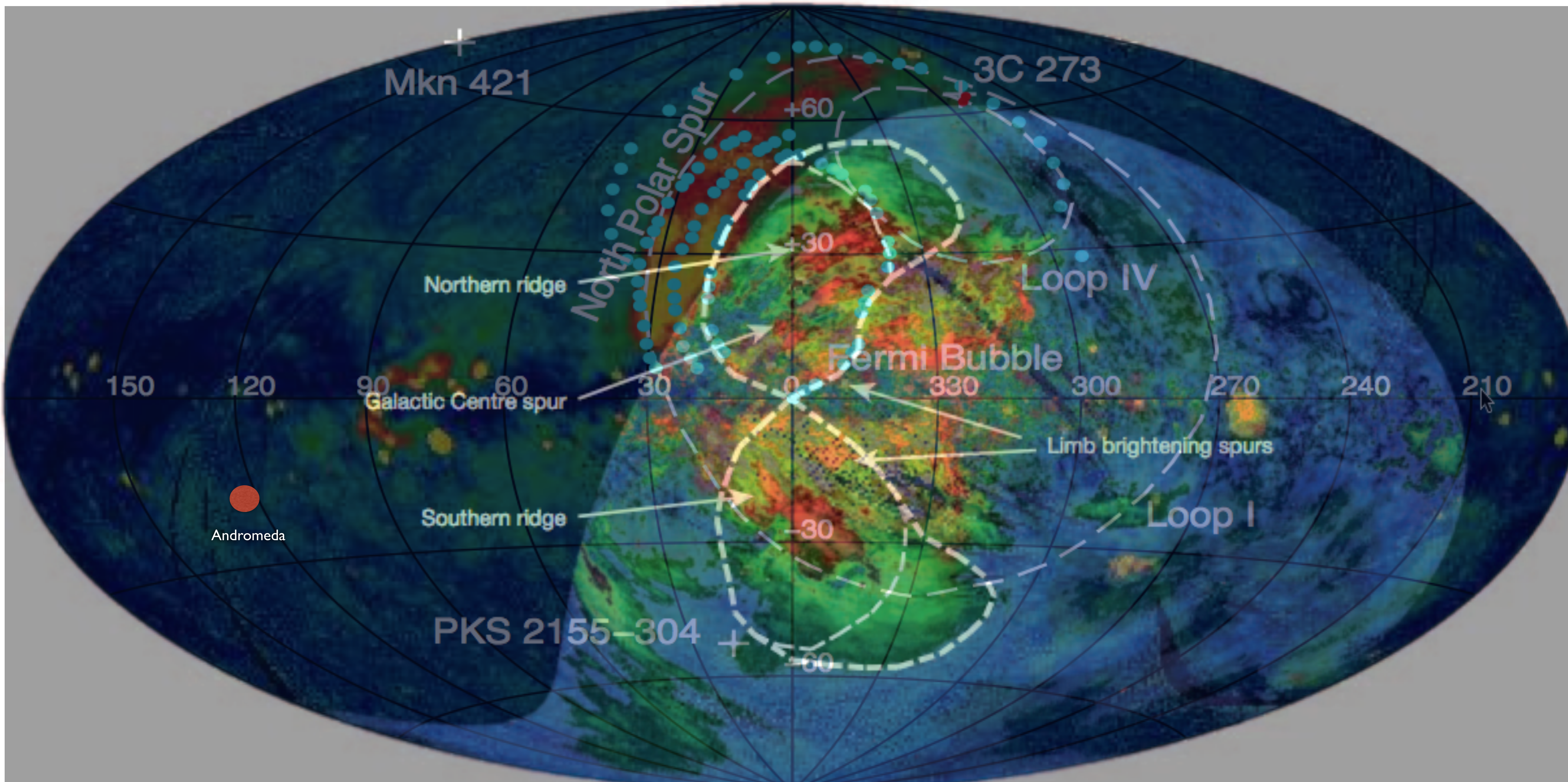


Casandjian2015

S-PASS 2.3 GHz
polarzd intensity
Carretti2013



A breeze from Andromeda?



Extra Slides

Where the game kicks off…

- In this talk: "Galactic center" (**GC**) = inner 300 pc (diameter) of Galactic plane
- GC sitting at bottom of Galactic gravitational potential

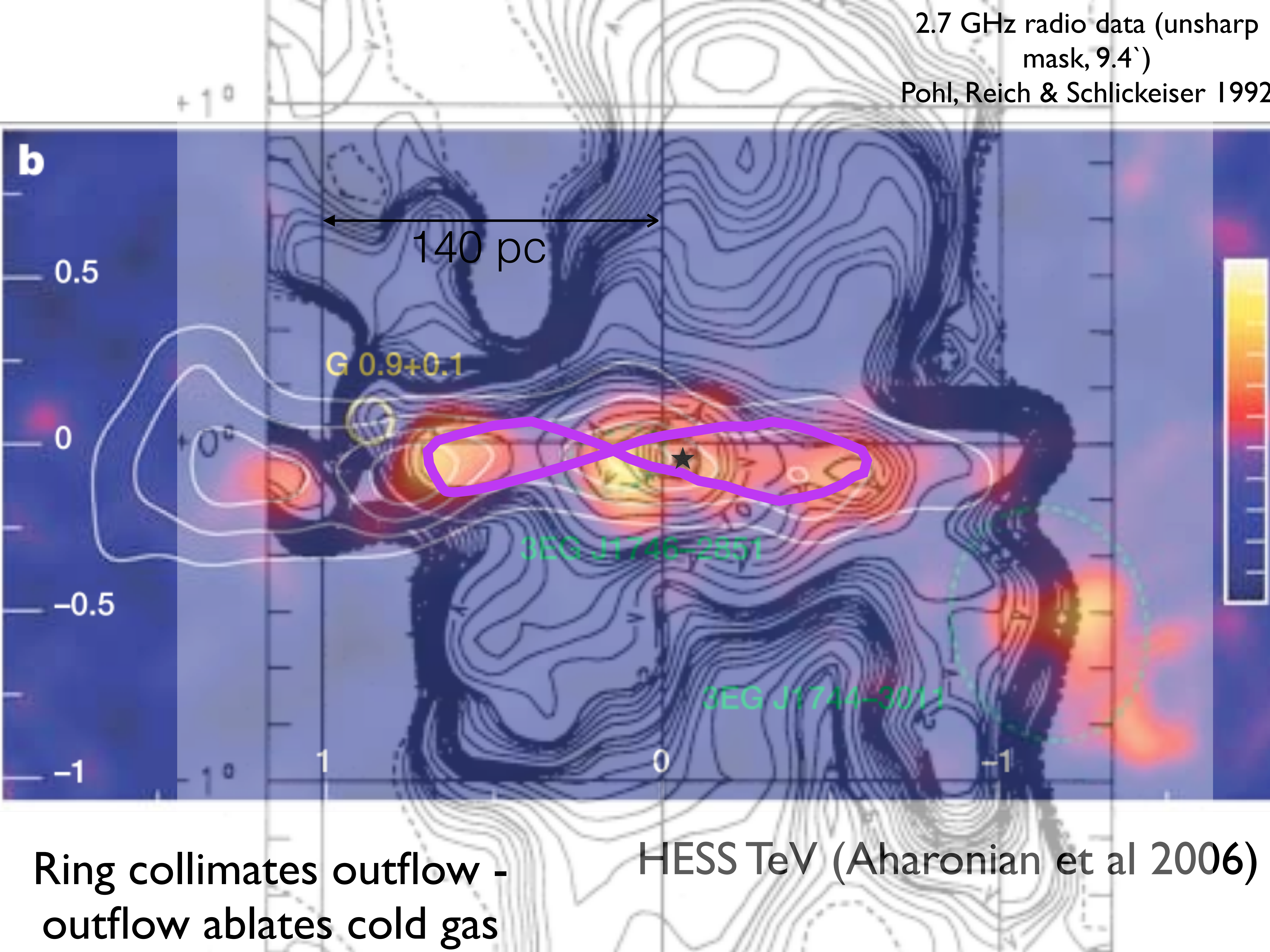
$\Rightarrow$ where the Galaxy's 4 million solar mass super-massive black hole (SMBH) lurks

$\Rightarrow$ where Galactic stellar density and star formation rate density reach a crescendo

Central Molecular Zone

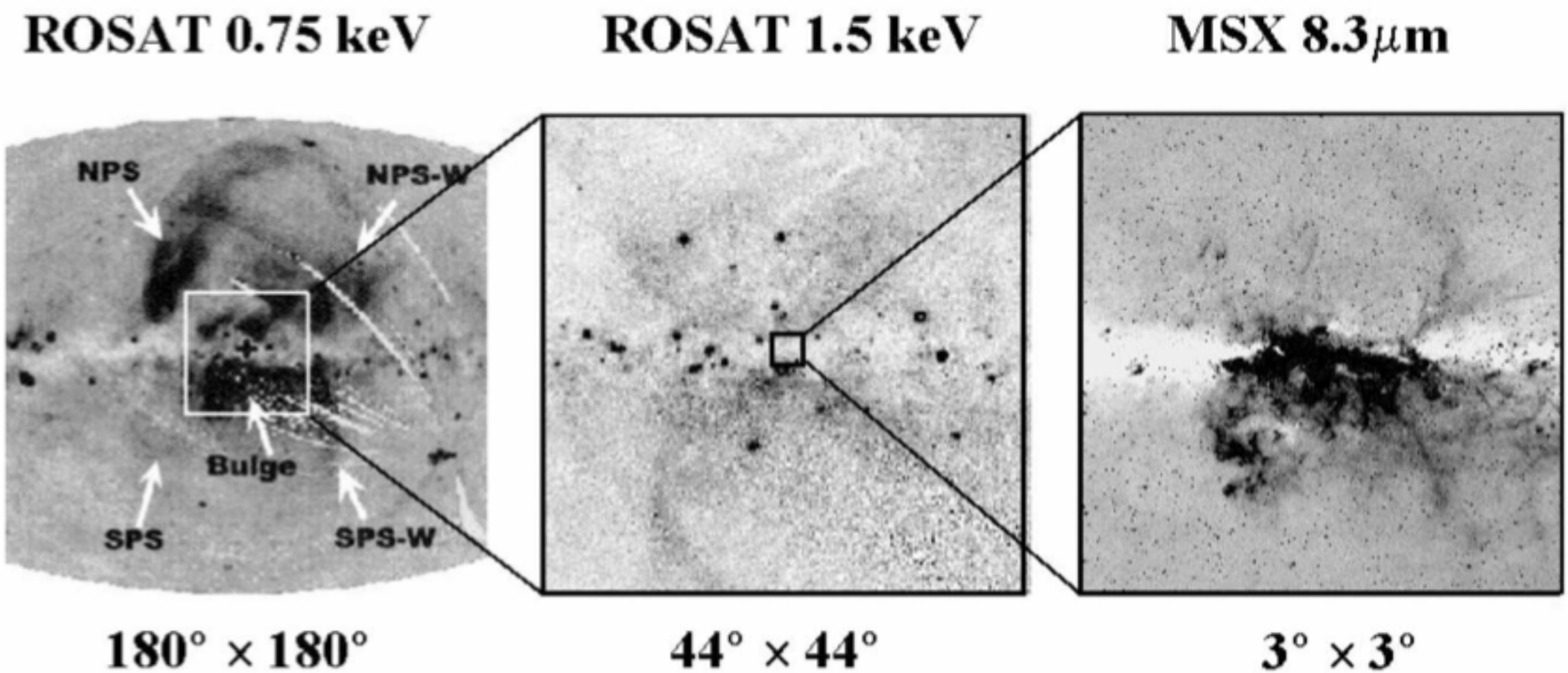
- ~30 million solar mass torus of H_2, ~5% of the Galaxy's H_2
- The torus hosts on-going, intensive, localized star-formation: ~5-10% of Galaxy's *massive* star formation
- SFR surface density over CMZ $\gtrsim$ **3 orders of magnitude** larger than mean in disk ($\partial_t \Sigma_* \sim 2$ $M_\odot$ yr^{-1} kpc^{-2}) and sustained…***should drive outflow***

2.7 GHz radio data (unsharp mask, 9.4`)
Pohl, Reich & Schlickeiser 1992



Ring collimates outflow - outflow ablates cold gas

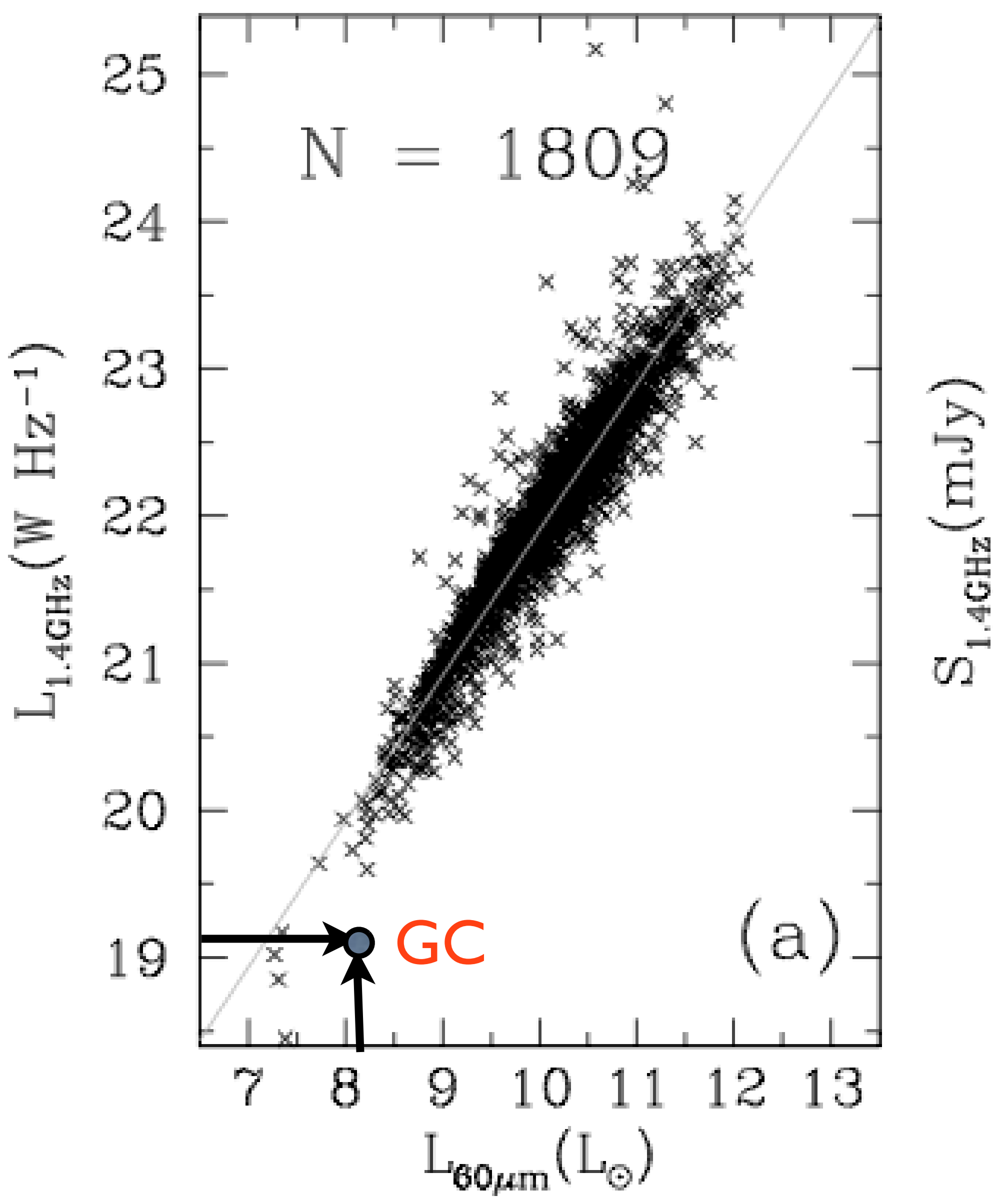
HESS TeV (Aharonian et al 2006)



Bland-Hawthorn & Cohen 2003

FIR-RC

Yun et al. 2001 ApJ 554, 803 fig 5



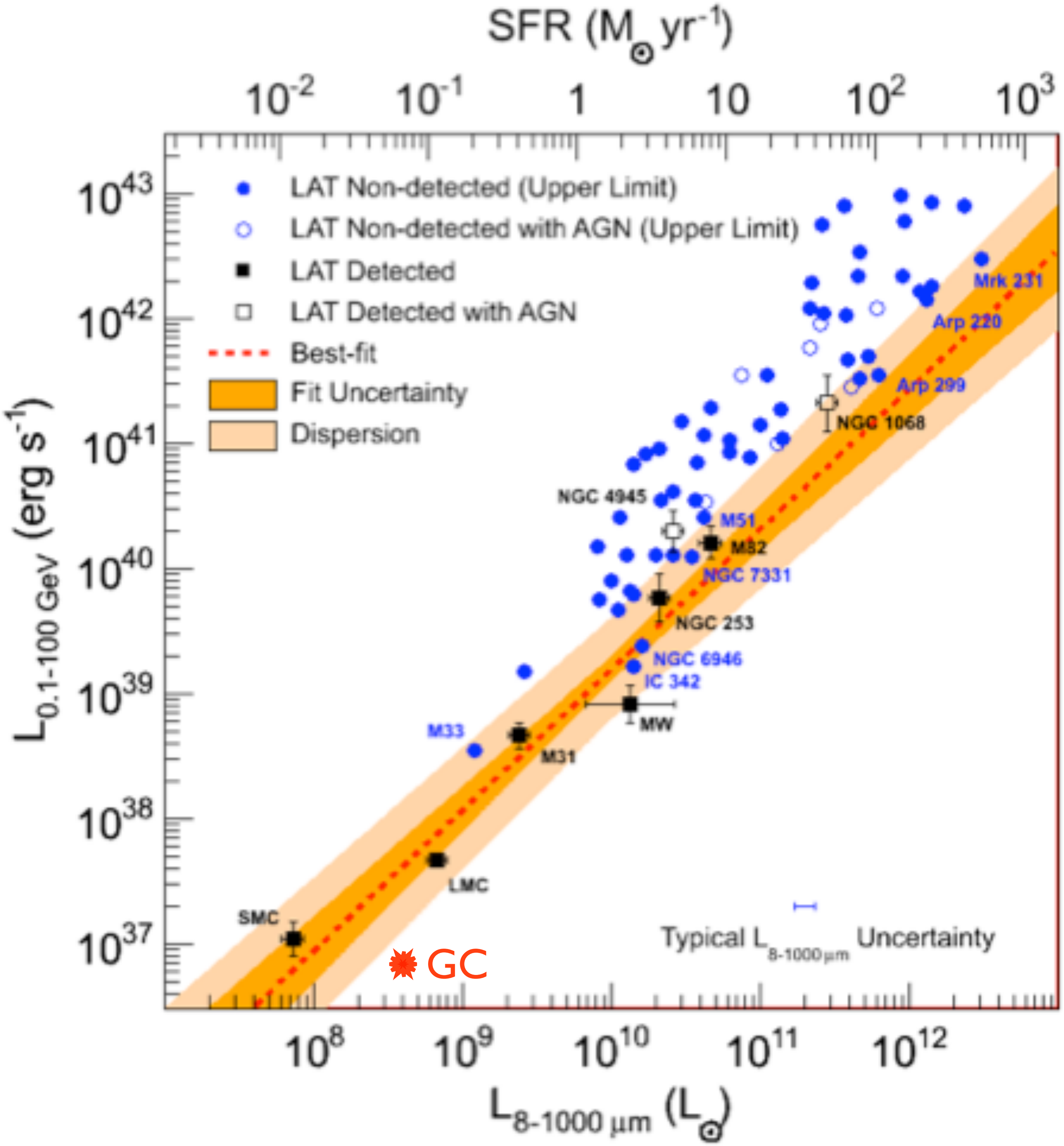
$L_{1.4\,GHz} = 1.2 \times 10^{19}$ Watt/Hz

$L_{60\mu m} = 1.3 \times 10^{8}\ L_{\odot}$

radio in deficit wrt expectation from FIR

system is 1 dex (> 4σ) off correlation

i.e. **GHz radio emission of region only ~10% expected**



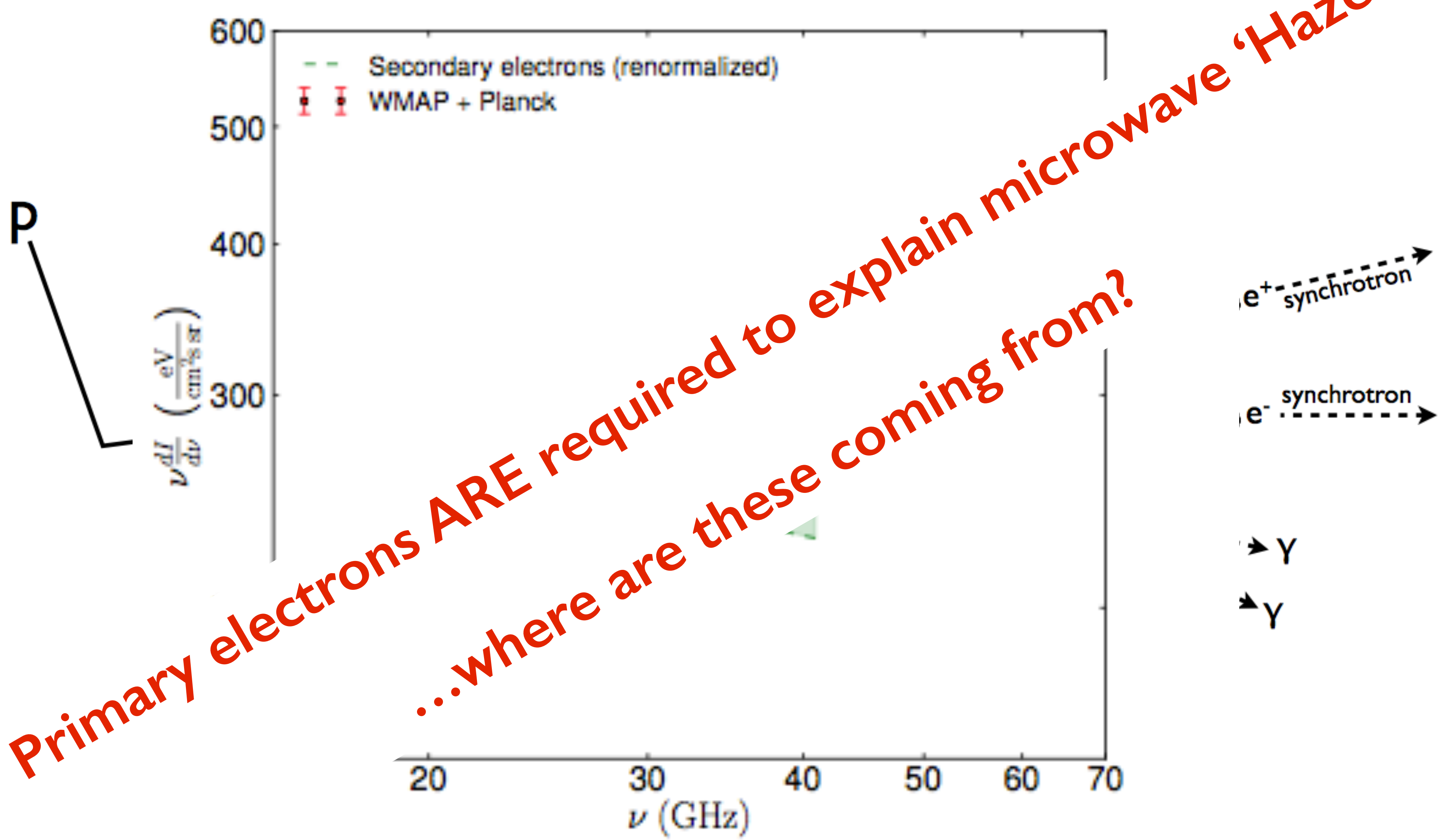
Ackermann et al. 2012 (*Fermi collab)*

Fig. 1. Gamma-ray luminosity (0.1-100 GeV) versus total IR luminosity (8-1000μm).

so, cosmic rays are being blown out of the GC

…what is the fate of the advected cosmic rays?

Synchrotron Phenomenology



Primary electrons ARE required to explain microwave 'Haze'

…where are these coming from?

Ackermann et al. 2014 *Fermi* collab

Giant Shocks in the Fermi Bubbles

- The microwave emitting (haze) electrons are carried into the downstream at ~300 km/s, reach 2 kpc beyond shock
- Resolved and 1-to-1 correspondence between age and distance from acceleration site ⇒ hard spectrum
- Explains luminosity, spectrum and extension of haze

Giant Shocks in the Fermi Bubbles

- The 2.3 GHz emitting electrons, cool more slowly and can reach Bubble edges
- Mixing/accumulation of different aged 2.3 GHz emitting electrons in thick target $\Rightarrow$ steep spectrum
- Explains luminosity, spectrum and extension of polarised 2.3 GHz emission

…*not necessarily*: Hadronic Emission from Filaments

Crocker, Bicknell et al. 2014, ApJL

- Bubbles' ~3 10^6 K plasma is thermally unstable
- t_{cool} ~ few 10^8 year ⟵ natural timescale
- fountain flow sets up steady-state plasma density:

$$n_{ss} \simeq \sqrt{\frac{k_B\, T_{\rm FB} \dot{M}_{\rm in}}{(\gamma-1)\Lambda[T_{\rm FB}] V_{\rm FB}\, \mu\, amu}}$$

$$\simeq 0.0055\ {\rm cm}^{-3} \left(\frac{\dot{M}_{\rm in}}{0.1\, M_\odot/{\rm year}}\right)^{1/2}$$

consistent with X-ray observations

Hadronic Emission from Filaments: few x 10^8 year timescale

Crocker, Bicknell et al. 2014, ApJL

- collapsing filaments adiabatically compress magnetic fields and cosmic rays
- filament collapse arrested when $P_{CR} + P_B = P_{pls}$
- filaments fall at terminal velocity back to plane
- can predict hadronic luminosity:

Hadronic Emission from Filaments

Crocker, Bicknell et al. 2014, ApJL

$$\begin{aligned} L_\gamma^{\rm pp} &\simeq 3/2\ 1/3\ f_{\rm bolo}\ \sigma_{\rm pp}\ \kappa_{\rm pp}\ c\ n_{\rm H}^{\rm fil}\ u_{\rm p}^{\rm fil}\ \ V_{\rm fil} \\ &\simeq \frac{3\ f_{\rm bolo}\ \sigma_{\rm pp}\ \kappa_{\rm pp}\ c\ \dot{M}_{\rm in}(k_{\rm B}\ T_{\rm FB})^2}{\Lambda[T_{\rm FB}]\ m_{\rm p}} \left(\frac{M_{fil}}{M_{pls}}\right) \\ &\simeq 3.4\times 10^{37}{\rm erg/s}\left(\frac{\dot{M}_{\rm in}}{0.1\ M_\odot/{\rm yr}}\right)\left(\frac{T_{\rm FB}}{3.5{\times}10^6\,K}\right)^2\left(\frac{M_{fil}}{M_{pls}}\right) \end{aligned}$$

Sanity Check